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Final Report

SCIENTIFIC IMPACTS OF PHENOMENA-ORIENTED RESEARCH SPONSORED BY AFOSR
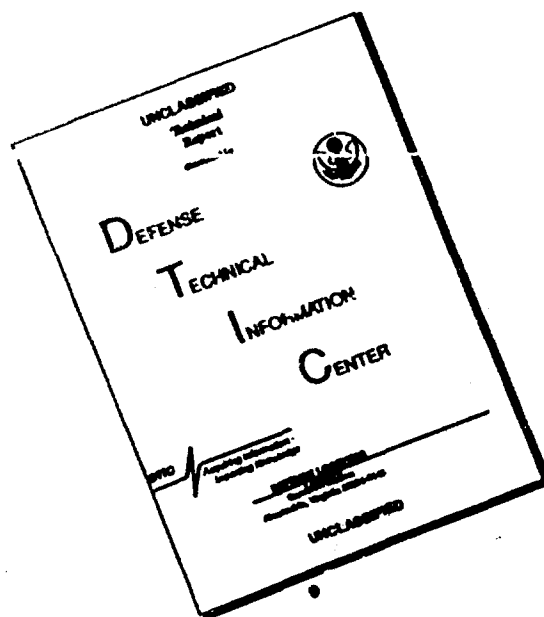
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ABSTRACT

This exploratory study has the purpose of developing and demonstrat-
ing methods of evaluating the scientific impacts of pioneering phenomena-
oriented research sponsored by a mission-oriented agency. Analysis of
research abstracts yielded an index of candidate research topics. Of
these, three were selected as meeting all criteria; of the three, whistlers
proved to contain the bulk of the scientific information.

Whistlers are audio-frequency radio signals resulting from the longi-
tudinal propagation of sferics in the exosphere. Their general character-
istics were fairly well understood prior to 1960; but work sponsored by
AFOSR in that year contributed materially positive identification of their
source, understanding of the laws of their propagation, and elicitation of
the information they yield about electron and proton concentrations at
altitudes of up to 4 earth radii. As verified by other means, notably
radio satellites, this information plays a pivotal role in understanding
the exosphere, the radiation belts, the magnetosphere, and the limitations
to earth-based radiolocation.

The study demonstrates the conclusion that working from scientific
effort to scientific and technological impact is a valuable adjunct to
analysis via the reverse path, and yields additional implications for the
study of these impacts.

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TABLES

Introduction

Three basic conceptions underlie the design of this research project:

1. The conventional linear sequential conception of the way in which
    science becomes technology is fallacious. The prevailing con-
    ception is that a scientific discovery immediately gets incor-
    porated in an invention, exploited in a new product that imme-
    diately displaces less advanced competitors. A more adequate
    conceptualization was originally advanced by Albert Shapero.[*]
    Scientific discoveries go into a "pool of knowledge" where they
    typically lie fallow for years or decades. Five years seems to
    be about the median fallow period today. Then an inventor
    demonstrates the feasibility of achieving a technological object
    by drawing on a new combination of scientific principles. This
    invention goes into a "pool of techniques" where it in turn may
    lie fallow for years or decades before being incorporated in a
    salable product; or it may take years or decades to reduce feasi-
    bility to practicality. In addition, a new product, even if it
    constitutes a major improvement in the state of the art, unless
    it solves a critical problem, goes into a "pool of components"
    drawn on by systems designers over a period of years or decades.
    In sum, although fundamental discoveries may lead to rapid
    exploitation and technological revolution, as in the case of
    minority carrier conduction in semiconductors, the more typical
    situation is one in which a variety of scientific discoveries are
    incorporated into inventions or innovations; a variety of inno-
    vations into a new hardware item; and a variety of hardware items
    into a new system; each step in the process involving a signifi-
    cant lag in time.

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* "Diffusion of Innovations Resulting from Research: Implications for
Research Program Management." Second Conference on Research Program
Effectiveness, ONR, July 27, 1965.

2. A mission-oriented organization such as the Air Force has at
least three valid reasons for sponsoring basic research not
directly related to its mission.*

   a. The agency may need to stay cognizant of developments in a
      scientific discipline, in case any of them should prove
      germane to its mission. One of the more efficient ways of
      maintaining this cognizance is by sponsoring research in the
      field, thus maintaining communication with a scientist who
      is au courant in it.

   b. The agency may want to ensure that the United States retains
      eminence or at least parity in the discipline, to prevent a
      potential enemy's exploiting a new scientific discovery
      before the U.S. can.

   c. Exceptionally, the agency may judge that an area of investi-
      gation is of enough scientific importance to be expedited;
      not for any foreseeable application, but for the sake of
      scientific progress, which in general can be expected to
      redound to the benefit of the agency.

      The first of these motivations, (a), entails but a modest
      level of support, typically less than one percent of the
      total national research effort. The second, (b), may require
      support of from one percent to ten percent of the total
      national effort. The pioneering research effort, (c),
      usually entails support of more than ten percent of the total
      national effort in the field.

3. The usual attempt to assess the value of basic research by
   starting with applications and searching for their origins in
   discovery or invention is inadequate alone. It needs to be

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* Joseph P. Martino, "The Use of Technological Forecasts for Planning
  Research," James R. Bright, ed., Technological Forecasting for Indus-
  try and Government, pp. 265 ff., Englewood Cliffs, N.J. Prentice-Hall,
  Inc., 1968.

supplemented, if possible, by an investigation starting with the scientific discovery and working forward to seek its scientific and technological consequences.

Objectives

This study has two objectives:

1. Development of a method for assessing the scientific and technological impacts of pioneering non-mission-related research efforts sponsored by AFOSR.

2. Application of this method in one or more specific instances as a contribution in support of the thesis that such research redounds to the benefit of the Air Force.

Method of Study

The starting point for this research effort was the Air Force Scientific Research Bibliography, Volume IV.* This volume contains 3048 abstracts of AFOSRY-sponsored research reported roughly in the calendar year 1960. (Some late-1959 research reports are included, and of the course the work reported on usually originated earlier; but Volume IV nonetheless represents an approximately one-year slice of AFOSR-sponsored research effort.)

The principal investigator marked the entries in the subject index to this volume in which he felt technically competent and had the corresponding abstracts xerographed and mounted on file cards. He then sorted the cards to eliminate the following categories from consideration:

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* G. Vernon Hooker, Doris C. Yates, Harvey D. Brookins, Joan E. Ralpin, and Parthenia A. Patrick (compilers). Special Bibliographies Section, Science and Technology Division, Library of Congress. Available from the Superintendent of Documents, U.S. Government Printing Office, or from the Defense Documentation Center.

1. Research performed under multiple sponsorship: typically AFOSR-NRL-ARO or either pair, sometimes with the addition or the substitution of NSF or the Bureau of Standards. In this exploratory effort, the attempt to determine the level of support of each agency in a multiple-sponsorship project was unwarranted; rigor dictated their elimination.

2. Research obviously related to the mission of the Air Force. Here the effort was to be rigorous without eliminating everything through real or fancied relatedness to the mission of the Air Force. For one example, elimination of everything in electronics and semiconductor physics on the grounds that the Air Force uses electronics and semiconductors was clearly unwarranted; but the Air Force has so clear a special interest in radar and missile telemetry that microwave antenna design must be adjudged mission related. For a second example, plasma physics is a broad and expanding field with applications ranging from the ionosphere to the sun; but boundary-layer problems relate obviously to re-entry vehicles and to hypersonic flight.

3. Mathematical studies of general applicability. In the first place, general mathematics is not what was contemplated under the term "phenomena-oriented research"; in the second, many of the papers had to do with computer applications, which relate directly with telemetry and guidance.

This elimination process left 109 studies. Because the original subject index proved inadequate for the purpose, the investigator constructed a new index for classifying these studies, guided by the following principles, formulated in order to secure a minimum vocabulary in the index:

1. All terms are substantives tolerable of being interpreted attributively. For instance, "elasticity" standing alone is a noun; "elasticity dynamics" forces the construing of "elasticity" as an adjective. English is tolerable of a pyramiding of nouns used attributively; hence "semiconductor impurity electron

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paramagnetic resonance" is readily understood as a succession of progressively larger categories in combination defining a restricted research area.

2. The only exception to the above is the use of the phrase "effect on" as a vocabulary term. Some such expression as "as affected by" would have been more logical but would not have been so unambiguously understood.

3. Generic terms and periphrases were substituted for technical terms and proper names: "sun" for "helio," "electrostatic effect on spectral lines" for "Stark effect."

4. In constructing the index, terms like "electromagnetic" were broken down into their kernels; but in the actual index the terms were recombined.

Each study was assigned an index title constructed according to these principles. A total of 73 terms were found necessary for this purpose; they appear in Table I, page 41. The index itself was constructed by listing alphabetically each of these titles under each of its terms; the result is Table II, page 42.

The purpose of this index is to secure a list of candidate topics for this study with the assurance that all relevant research projects are included. Through inspection of this index, the following topics (not themselves necessarily index entries) were selected:

Lasers and masers
Semiconductor compounds
Microwave heliography
Riometry (radio noise measurements on the ionosphere)
Millimeter-wave generation, detection, and spectroscopy
Radio star scintillation
Whistlers

A research assistant copied xerographically all abstracts apparently
pertinent to these topics listed in Physics Abstracts and Electrical Engi-
neering Abstracts[*] as published in the United States with a 1960 publica-
tion date. The principal investigator chose those that were actually
germane. If this process yielded more than ten times as many abstracts
as appeared in the AFOSR Bibliography, the topic was eliminated. This
study was to be of "pioneering research," as defined in the Introduction;
and pioneering research entails that AFOSR sponsor at least 10 percent of
the American research effort in the field.

Three topics remained: riometry, microwave heliography, and whis-
tlers. The three are related in that all have to do with ionosphere
propagation, particularly fine structure of the exosphere. The principal
investigator and the project monitor agreed to carry the three topics
through the rest of the study together. In fact, however, the bulk of
the scientific information was in the whistler studies; the other two
topics covered primarily research instrumentation and methods.

The remaining sections of this report give, in succession, a general
description of the earth's atmosphere; an introduction to radio propaga-
tion in the atmosphere; a discussion of whistlers and the exosphere,
including the state of knowledge prior to 1960; contributions of AFOSR-
sponsored studies in 1960, and their scientific and technological impacts;
and conclusions.

General Description of the Atmosphere[†]

The atmosphere can be considered to have three major divisions, with
some overlap: the homosphere, 0-100 km; the ionosphere, 60-600 km; and
the exosphere, extending from perhaps 500 km to the outer extremities of

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[*] Each published monthly by the Institution of Electrical Engineers,
London.

[†] C.O. Hines, I. Paghis, T. R. Hartz, and J. A. Fejer, eds., Physics of
the Earth's Upper Atmosphere, Englewood Cliffs, N.J., Prentice-Hall,
Inc., 1965.

the earth's magnetic field. The dominant physical and chemical processes in the three regions are widely different from one another.

The homosphere -- This is the region of turbulence, weather, and life. Gas molecules in this region of the atmosphere collide with one another so frequently that the various constituents stay thoroughly mixed: aside from temporary local variations, the atmosphere is homogenous in this region; hence the name homosphere.

In the lowest 15 km or so of the atmosphere, the temperature decreases with altitude to a minimum of about 200°K (-75°C). This temperature lapse carries with it the possibility for thermal instability, with light warmer air rising and displacing cooler upper air. This instability, along with uneven heating of the lower air by land and water masses, evaporation and precipitation of water, and the rotation of the earth, produces weather.

This lowest portion of the atmosphere is called the troposphere. At its top, the tropopause, the temperature is no longer decreasing with altitude; still higher, in the stratosphere, the temperature increases with height. Here there is no turbulence; the air remains stratified, as in a "temperature inversion" near the surface of the earth.

The stratosphere has its upper limit and maximum temperature in the ozonosphere, a relatively shallow region at an altitude of perhaps 35 km where the sun's near ultraviolet light dissociates molecular oxygen into atomic:

$$O_2 \rightarrow 2O, \tag{1}$$

and the nascent oxygen atoms combine with normal oxygen molecules to form ozone:

$$O + O_2 \rightarrow O_3. \tag{2}$$

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The energy released through these reactions raises the temperature of the ozonosphere to about that at the surface of the earth.

Above the ozonosphere, in a region called the mesosphere, the temperature again lapses, reaching a minimum at the mesopause, just below 100 km. But the ionospheric behavior of the mesosphere is probably more significant than the behavior of its neutral constituents.

The homosphere is under the control primarily of gravity and the gas laws. The change in pressure with height is due to each layer's adding its weight per unit area to the pressure that it transmits from above:

$$dp = - \rho g \, dh, \tag{3}$$

where

  p is the atmospheric pressure at height h,

  g is the acceleration due to gravity, and

  ρ is the local mass density of the atmosphere.

The density ρ can be eliminated through use of the general gas law in the form:

$$p = \rho kT/M;$$
$$\rho = pM/kT;$$
$$dp/p = - (Mg/kT)dh, \tag{4}$$

where

  M is the mean molecular mass of the atmosphere's constituents,

  k is Boltzmann's constant, $1.38(10)^{-23}$ Joule/$^\circ$K,

  T is local atmosphere temperature, $^\circ$K.

In a homogenous, isothermal atmosphere, this equation reduces to:

$$dp/p = - dh/H, \tag{5}$$

where $H = kT/Mg$ is the so-called "scale height" of the atmosphere. This
equation integrates immediately to yield the law of pressure lapse with
height in the atmosphere:

$$p = p_o \, e^{-h/H},\tag{6}$$

where p_o is the pressure at the surface of the earth. Although the tropo-
sphere is not isothermal, its temperature varies much more slowly with
altitude than its pressure, and therefore Equation (6) describes the vari-
ation of pressure with height quite accurately over regions of moderate
extent.

The scale height H is the change in altitude over which the pressure
changes by the factor e (approximately 2.718). It is also what the
height of the atmosphere would be if it could be kept homogenous and iso-
thermal and at the uniform p_o. At the surface, H is about 8.5 km; it
varies between about 5 and about 10 km in the homosphere.

At the surface of the earth, the mean free path of the air molecules--
the distance, on the average, that an air molecule moves between collisions
--is a small fraction of a millimeter. It increases with altitude until,
at 100 km altitude, it is of the order of a meter. Between about 100 and
about 120 km in altitude, therefore, is a region in which the molecular
mean free path approaches the dimensions of "ordinary" objects--airplanes,
re-entry vehicles, and meteorites. An airfoil can no longer build up a
pressure differential to secure lift, because pressure depends on multiple
interactions between molecules, and therefore mean free paths orders of
magnitudes smaller than the airfoil. A meteorite or a re-entry vehicle,
on the other hand, can in this region begin to build up a pressure cap
ahead of itself, to heat it up and to slow it down. This "slip region"
marks the upper boundary of the sensible atmosphere.

The ionosphere -- X rays and gamma rays in the sun's radiation can
ionize atoms and molecules in the earth's atmosphere. Given an atmos-
phere in which the pressure, and therefore the number density of atoms
and molecules, varies exponentially with height, as described by

Equation (6), radiation entering the atmosphere from above encounters an increasing number of ionizable particles per unit length of path, and is therefore increasingly absorbed. The amount of ionization per unit volume therefore reaches a peak at some characteristic altitude in the atmosphere.

The number q of ion pairs per unit volume per unit time produced by an incident ionization of local intensity S is:

$$q = nSA = - dS/ds, \qquad (7)$$

where

ds = dh sec χ is the increment of path length traversed by the radiation;

χ is the angle between the radiation path and the vertical;

$n = n_o e^{-h/H}$ is the local number density of the ionizable species; and

n_o is the extrapolated number of this species at the surface of the earth.

Substitution of these relations into Equation (7) yields:

$$dS/S = -(n_o A \sec \chi) e^{-h/H} dh,$$

which can be integrated immediately to yield,

$$S = S_o \exp \left[(AHn_o \sec \chi) e^{-h/H} dh \right]. \qquad (8)$$

Substitution of this value for S back into Equation (7) gives:

$$q = nSA = An_o S_o \exp \left[-h/H + (AHn_o \sec \chi) e^{-h/H} \right] \qquad (9)$$

In this equation, if we substitute $z = (h - h_o)/H$, in effect measuring altitude in H units from the altitude of maximum ionization q_o, then;

$$q = q_o \exp[1 + z - e^{-z} \sec \chi]. \qquad (10)$$

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Equation (10) gives the rate of production of ion pairs in a plane homogenous isothermal ionospheric region. If we assume in addition that diffusion of ions out of the region does not significantly decrease the number of ions, and that the number of ion pairs is significantly less than the number of neutral atoms and molecules, then the change in number N_e of electrons per unit volume is given by:

$$dN_e/dt = q - \alpha N_e^2 - \beta N_e, \qquad (11)$$

where

α is the electron-ion recombination coefficient, and

β is the attachment coefficient of electrons with neutral atoms or molecules.

(The probability of electron-ion recombination is proportional both to N_e and to N_1, the positive-ion number density; but $N_1 \doteq N_e$. On the other hand, the number of neutral atoms and molecules available for attachment is substantially independent of N_e.)

Under equilibrium conditions, $dN_e/dt \doteq 0$. If, in a given ionosphere region, recombination is the dominant mechanism of electron loss, then, from Equations (10) and (11):

$$N_e^2 = N_o^2 \, Ch(z); \qquad (12)$$

but if attachment is dominant,

$$N_e = N_o \, Ch(z); \qquad (13)$$

where

$$Ch(z) = \exp(1 + z - e^{-z} \sec \chi). \qquad (14)$$

At various times there appear to be five distinct regions in the ionosphere, called the C, D, E, F_1, and F_2 layers.

Evidence for existence of the "C layer" comes mostly from phase characteristics of LF radio propagation. In the daytime, it is thought to have a quasi-peak electron intensity at about 70 km in altitude. It is not a Chapman layer, but appears to be formed by ionizing cosmic rays. Although cosmic rays are essentially constant in intensity throughout the day and night, the resulting electrons are at night rapidly removed through attachment to neutral oxygen atoms:

$$e + O_2 \rightarrow O_2^-;\qquad(15)$$

but, in the daytime, ultraviolet sunlight dissociates these ions as rapidly as they are formed.

The D region, with a quasi-peak electron intensity at about 85 km altitude, is complex in its formation but appears to behave substantially like a Chapman layer. Ionization of the D region under normal conditions appears due to two mechanisms: Lyman α radiation, which does not vary with the sunspot cycle, ionizing traces of nitrous oxide (NO); and hard X ray radiation, which follows the sunspot cycle, acting on N_2 and O_2. Under abnormal conditions, in addition to greatly increased hard X ray flux from the sun, energetic protons may enter the polar D layer poleward from the auroral zone, and energetic electrons trapped in the exosphere can stop and can produce additional ionization in the D region at auroral latitudes.

The E region, with its peak ionization near 110 km altitude, is in the "slip region" of the atmosphere. The mixing process that maintains homogeneity in the homosphere is no longer effective; in particular, N_2 and O_2 are photodissociated into N and O in the E region. Soft X rays (10-100 A) ionize N_2, O_2, N, and O more or less indiscriminately, but the N_2^+ recombination coefficient is so much greater than that for the other three that there is very little N_2^+ in the E region, and the region is basically an α-type Chapman layer. In addition, a variety of ionization processes, including impacts of micrometeorites, and ion transport phenomena, superimpose "sporadic E" electron clouds on the regular E-layer ionization.

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Above the E region is the F_1 region which, like the E region, appears
to be basically an α-type Chapman region. (Through the E and F_1 region,
the scale height H is gradually increasing, with increasing temperature
and decreasing mean molecular weight.) The principal atmospheric constit-
uents in the F_1 region are O, N_2, O_2, N, and NO, in that order. As in
the E region, solar ultraviolet is the principal ionizing mechanism, and
recombination with positive ions the principal electron loss mechanism.

The D, E, and F_1 regions of the ionosphere vary in electron density
and in height of maximum electron density with sun angle as Chapman layers
would. (The sun's zenith angle is, of course, a function both of time of
day and time of year, and also of altitude: the ionosphere is illuminated
significantly before sunrise and significantly after sunset.) At dusk,
these layers disappear with a lag ranging from milliseconds in the D re-
gion to a half-hour or so in the F_1 region. They are, therefore, normally
absent through most of the night.

The F_2 region, with its peak electron density varying from 250 to
500 km, by contrast with the lower layers is present throughout the night.
(It is conventionally assumed to merge with the F_1 layer to form a single
"F layer.") Although it sometimes appears to be a β-type Chapman layer,
its peak electron density and altitude do not follow the Chapman laws,
often moving counter in sense to the movements of the lower layers. For
these reasons, magnetohydrodynamic ion movements, horizontally and from
above and below, are assumed to play significant roles in determining the
structure of the F_2 region.

The exosphere -- In the upper regions of the F_2 layer, the mean free
paths of neutral atoms and molecules become comparable in size to the
local scale height. Above this altitude, the neutral atoms and molecules
no longer behave like a gas, but largely follow ballistic trajectories
without a significant number of collisions: projected upward by colli-
sions with other particles at lower levels, they arc across the exosphere,
following elliptic trajectories back into the denser regions below or
occasionally acquiring enough kinetic energy to leave the earth's gravi-
tational field.

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But a significant fraction of the exosphere's constituent atoms and molecules are ionized, and their behavior is greatly different from that of the neutral species. Their collision cross-section is much greater than that of neutral species, so they continue to experience many collisions per scale height throughout the exosphere. Any tendency toward separation of positive ions and electrons is suppressed by the Coulomb force between them, many orders of magnitude greater than gravitational attraction or their usual kinetic energy. Among other things, the lighter electrons buoy up the heavier positive ions, effectively doubling their scale height. And the movement of charged particles in the exosphere is dominated by the earth's magnetic field; the exosphere is a plasma obeying magnetohydrodynamic laws.

The temperature of the ionosphere rises almost linearly from its minimum in the mesopause to about 1500°K at the peak of the F region. In the exosphere, temperature is not a valid concept for neutral particles. It is a valid concept, however, for ions; and they appear to remain at about 1500°K throughout the exosphere. Besides the thermal particles, however, there are highly energetic charged particles (protons and electrons) trapped in the exosphere at temperate latitudes by the earth's magnetic field, in a manner discussed later (page 25).

Prior to rocket soundings commencing with the International Geophysical Year, subsequent satellite soundings, and the whistler research reported on in this study, knowledge of the exosphere was scant, indeed. One could postulate an exponentially decreasing atmospheric density, from perhaps $10^8/cm^3$ at the peak of the F_2 layer to perhaps $30/cm^3$ known from astronomy to exist in the interplanetary space of the solar system; but its constituency, scale height, and behavior were largely unknown.

Radio Propagation in the Atmosphere[*]

Radio waves propagated through the atmosphere are affected by a wide variety of scattering and fading effects due to local anomalies and movements both of neutral and of charged particles. These are superimposed on the more or less static and predictable large-scale effects in the major atmospheric regions just described.

Electrons and ions react much more vigorously with radio waves than do neutral species; and electrons, because of their much smaller mass, interact much more vigorously than other ions. Atmospheric radio propagation is, therefore, almost entirely the study of electron-wave-field interactions. These interactions are of three kinds:

1. Electrostatic interaction between electron and electromagnetic field. A linearly polarized radio wave, for example, has an electric field in the form $E = E_o e^{j\omega t}$ in its plane of polarization. This field accelerates electrons in the region through which the wave is propagated:

$$F = m \, dv/dt = qE_o e^{j\omega t};$$

$$v = (qE_o/m) e^{j\omega t}/j\omega. \tag{16}$$

This oscillatory motion of the electron constitutes a radiating dipole antenna, but its radiation is out of phase with the incident field E because of the $j\omega$ in the denominator. The two fields combine to reduce the index of refraction n in the ionosphere in accord with the Appleton-Hartree formula:

$$n^2 = 1 - Ne^2/\epsilon_o m\omega^2, \tag{17}$$

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* Olof E. A. Rydbeck, On the Propagation of Radio Waves, Gothenburg, Sweden, Chalmers Institute of Technology, 1944.

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where

n is the electron density,

e is the electron charge,

ϵ_o is the free-space dielectric constant,

m is the electron mass, and

ω is the wave angular frequency.

By Snell's Law, a wave entering a region of increasing ionization is bent away from the normal, because Equation (17) yields an index of refraction less than unity. This is the mechanism that "reflects" high-frequency radio waves in the ionosphere, making long-distance shortwave radio communication possible. Equation (17) can also be written in the form:

$$n^2 = 1 - \omega_o^2/\omega^2, \tag{17'}$$

where $\omega_o^2 = Ne^2/\epsilon_o m$ is the local angular plasma frequency.

2. Interaction between wave, electron, and magnetic field. The velocity of an electron moving in a uniform magnetic field can be resolved into two components, one along the field and one perpendicular to it. The magnetic field has no effect on the parallel component of the electron's velocity; it remains unchanged. The electron's charge and velocity component perpendicular to the field constitute a current flowing across the field. In accord with the dynamo rule, this current element experiences a force tending to move it perpendicular both to itself and the field. In this way, the electron is continually deflected and travels in a circle as seen in a plane perpendicular to the field. The centripetal force exerted by the field must equal the centripetal acceleration of the electron in its orbit:

$$Bev = mv^2/r, \tag{18}$$

whence

$$v/r = Be/m = \mu_o He/m = \omega_H, \tag{19}$$

where

v is the perpendicular component of the electron's velocity,

r is the radius of the electron's orbit,

$B = \mu_o H$ is the earth's magnetic induction, and

μ_o is the magnetic permeability of free space.

As noted, the component of the electron's velocity along the magnetic field is unchanged, and the component perpendicular to the field is changed in direction but not in magnitude. The kinetic energy of the electron is therefore unchanged; but it is constrained to spiral about the magnetic field direction.

An electrostatic field parallel to the magnetic field does not interact with that field; it can accelerate an electron or ion indefinitely along the field lines. For this reason, the conductivity of a plasma is very high along the magnetic field; electrons and ions move rapidly to neutralize any impressed electrostatic field parallel to the magnetic field.

For insight into the nature of the interaction of a transverse electrostatic field with the magnetic field and an electron, rewrite (18) in terms of x and y components, where OX and OY are mutually perpendicular axes also perpendicular to the magnetic field:

$$F_x = m \, dv_x/dt = - Bev_y;$$
$$F_y = m \, dv_y/dt = Bev_x. \tag{20}$$

Solve the latter equation for v_x:

$$v_x = (m/Be) \, dv_y/dt: \tag{21}$$

differentiate, substitute in the first member of (2), and solve for d^2v_y/dt^2:

$$d^2v_y/dt^2 = - (Be/m)^2 v_y. \tag{22}$$

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Let

$$v_y = v_o \sin \omega t;$$

$$dv_y/dt = \omega v_o \cos \omega t;$$

$$d^2 v_y/dt^2 = - \omega^2 v_o \sin \omega t = - \omega^2 v_y; \qquad (23)$$

substitute the result in (22):

$$\omega_H = Be/m, \qquad (24)$$

in agreement with Equation (19). From (21) and (23),

$$v_x = v_o \cos \omega t,$$

demonstrating again, with v_y, that the motion is uniform circular.

Now postulate a constant force F_1 acting on the electron in the positive direction. At the same time, change to a moving coordinate system by defining $u_y = v_y - F_1/Be$. Then:

$$F_x = m \, dv_x/dt = - Bev_y + F_1 = - Be(u_y + F_1/Be) + F_1$$

$$= - Beu_y;$$

$$F_y = Bev_x. \qquad (20')$$

which are the same in form as Equations (20): the electrons spiral around a line, parallel to the direction of the magnetic field, moving perpendicularly to the direction of F_1 with a drift velocity $v_d = F_1/Be$.

If the force F_1 is due to an electrostatic field, then electrons and ions will drift in the same direction: the direction of the force exerted by the electrostatic field will be opposite for the electron and ion, but so will the force Bev due to the magnetic field. But gravity acts in the same sense on both ions and electrons, and so they tend to drift apart: electrons west and positive ions east.

The fact that the overall motion induced in an electron in a magnetic field by a transverse electrical field is perpendicular to that field, considerably complicates the propagation of an electromagnetic wave in the magnetoionosphere. Instead of Equation (17), the index of refraction n becomes, in such a region,

$$n^2 = 1 - \frac{X}{1 - Y^2 \sin^2 \theta/2(1-X) \pm [Y^4 \sin^4 \theta/4(1-X)^2 + Y^2 \cos^2 \theta]^{1/2}} , \quad (17'')$$

where $X = (\omega_o/\omega)^2$, $Y = \omega_H/\omega$, and θ is the angle between the ray path and the magnetic field.

The $\pm$ in the denominator of Equation (17'') gives rise to two independent modes of propagation for a wave at a given frequency entering an ionized region at a given angle to the magnetic field. A linearly polarized wave generally splits into two oppositely-rotating elliptically polarized waves. In the real ionosphere, where there are both systematic and random variations in electron density, the recombination of these two waves is random in phase and amplitude--one cause of the notorious "fading" of long-distance radio signals.

3. Effects of electron collisions on magnetoionic radio propagation. The preceding two sections ignored interference between species in the atmosphere, and the results gave no indication of attenuation of the wave. In fact, the electron accelerated by the electromagnetic wave may collide with another particle--electron, ion, or neutral atom or molecule. Whether the electron either bounces elastically off the other particle or is captured by it, it is no longer moving in a path determined by the incident radiation, and it therefore dissipates, in the form of heat, some of the energy contained in the incoming radio wave.

It is usually assumed that the energy abstracted from the radio wave is not sufficient to raise the temperature either of the electrons or of the region as a whole. (This assumption is not always valid: in the so-called "Luxembourg effect" a powerful low-frequency radio station modulates the temperature of the ionosphere above it. The attenuation of a

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high-frequency wave passing through that region varies with the temperature; so the high-frequency signal arrives with the modulation of the low-frequency station superimposed on its carrier.) When that assumption is valid, the local electron collision frequency ν is substantially constant, and the attenuation coefficient K is given by:

$$K = \omega_H^2 \, \nu/2cn[(\omega \pm \omega_H \cos \theta)^2 + \nu^2], \qquad (25)$$

and the field strength of a wave that has passed through an attenuating region is given by $E(s) = E(0)e^{-\int K\,ds}$.

If the collision frequency ν is either relatively very small or very large, the absorption K is very small. Many collisions per cycle prevent the electrons' acquiring significant energy from the radio wave before having their velocities randomized by collision; many cycles per collision is equivalent to relatively rare extraction of energy from the wave by the randomizing process. When $\nu \gg |\omega \pm \omega_H \cos \theta|$, $K = \omega_H^2/2cn\nu \sim 1/\nu$. When $\nu \ll |\omega \pm \omega_H \cos \theta|$, $K = \omega_H^2/2cn(\omega \pm \omega_H \cos \theta)^2 \sim \nu$. When $\nu = \omega = \omega_H$, $\nu/10cn \lesssim K \lesssim \nu/2cn$. Under these last conditions, there is a broad maximum of the rate of absorption of the radio wave; this occurs in the daytime in the standard broadcast band in temperate latitudes and is due to ionization and collision in the D region of the ionosphere.

At higher frequencies, attenuation decreases with the square of the frequency; the radio wave may be able to pass through the D layer with relatively little absorption and be reflected, with little absorption, in the E or F regions. The least-absorbed frequency is the highest completely reflected from the ionosphere.

Still higher frequencies may be scattered forward from irregularities in neutral-molecule densities in the troposphere, or in electron densities in the ionosphere. These scattering mechanisms greatly attenuate the forward-scattered radio wave, but these higher frequencies have compensating advantages: less congestion in the radio spectrum and higher directivity achievable with relatively small antennas.

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Microwaves pass through the atmosphere with relatively little attenuation (except for the attenuation in clouds at shorter wavelengths used in weather radar), but tropospheric turbulence and ionosphere electron clouds limit the precision achievable in position measurement using microwaves. Wavelengths shorter than 1 cm (millimeter waves and shorter) are absorbed by molecular and atomic reasonances of the atmospheric constituents. This absorption varies with wavelength in a complex manner.

Toward the other end of the radio spectrum, in the low-frequency (LF) band between 30 and 300 kc/s, the radio wave is guided along the surface of the earth by currents induced in its surface, as well as reflected from the lower ionization in the ionosphere. In the VLF band (3-30 kc/s), the radio wavelength is comparable in size to the distance between earth and ionosphere, and radio waves are ordinarily propagated in a waveguide mode.

Exceptionally, however, a VLF or ELF (300-3000 c/s) signal can travel through an ionized region along a magnetic field of force. If in Equation (17″) $Y^4 \sin^4 \theta / 4(1-x)^2 \ll Y^2 \cos^2 \theta$, $n^2 \doteq 1 - X/(1 \pm Y \cos \theta)$; this is the so-called quasilongitudinal (QL) approximation. If in addition $X \gg Y \cos \theta \gg 1$, then:

$$n^2 \doteq \mp X/Y \cos \theta = \mp \omega_o^2 / \omega \omega_H \cos \theta. \qquad (26)$$

When $\theta = 0$, $\cos \theta = 1$. Only the + sign in (26) yields a real index of refraction and hence a possible mode of radio propagation. Since $n \gg 1$, the velocity of wave propagation in this mode is much less than in a vacuum; and, since n^2 is inversely proportional to frequency, the wave velocity is proportional to the square root of frequency. In fact, the time t taken for a signal to traverse a path P is given by:

$$t = (1/2c\omega^{1/2}) \int_P \omega_o \, ds / \omega_H^{1/2}, \qquad (27)$$

so that a signal originally composed of several simultaneous frequency components will consist, after traversing an ionized region in this mode,

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of a series of signals spread out in time as well as in frequency: the
high-frequency components will arrive first and the low-frequency last.

Whistlers and the Exosphere

Prior to the space age, the two major methods of exploring the iono-
sphere were through analysis of the phase characteristics of long-distance
low-frequency and medium-frequency radio signals and pulse soundings at
medium and high frequencies using the ionosonde developed by Breit and
Tuve. These methods had a common limitation: they were blind to condi-
tions above the maximum ionization density in the ionosphere.

There had been some rocket soundings of the ionosphere between 1945
and 1959, but the results tended to give a very detailed picture of local
ionosphere conditions rather than additional information on the large-
scale characteristics of the ionosphere. The early rocket soundings were
intended primarily to verify conclusions arrived at on the basis of iono-
sonde data. Often, in fact, the rocket itself disturbed conditions in
its immediate vicinity enough to make calibration and correction of its
findings by concurrent ionosonde data necessary.

No ionosonde measurements of the ionosphere from satellites--so-called
"topside sounder" measurements--had been made by 1960. The initial satel-
lite measurements of intense corpuscular flux out to 16 earth radii had
been made, leading to the postulation of the Van Allen radiation belts;[*]
but their detailed structure and etiology were as yet unknown.

Except for these early rocket and satellite soundings, all the infor-
mation about ionization in the exosphere available in 1959 came from
whistlers. The following three parts of this section discuss the infor-
mation available in 1959, contributions to the body of knowledge made by
research reported in 1960 and sponsored by AFOSR, and implications of
those contributions for subsequent exploration of the exosphere.

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[*] Van Allen, J.A., and L.A. Frank, "Radiation Around the Earth to a
Radical Distance of 107,000 Kilometers," Nature, 183 (1959) 430.

Knowledge of whistlers in 1959--If one connects a sensitive, low-noise audio (15-15,000 c/s) amplifier to a long horizontal antenna and connects the amplifier output to headphones or a loudspeaker, one hears primarily static properly so-called: the impulse noise generated by lightening strokes, called in radio "sferics" (short for "atmospherics"). In a temperate zone, the frequency of these impulses will be at a maximum if the antenna is pointed toward the equator, where thunderstorms are most frequent and intense.

But along with this static will come a variety of musical and quasi-musical sounds. The most frequent of these sounds are "whistlers." A typical whistler is a musical tone sliding from perhaps 1500 c/s to about 300 c/s and then disappearing, but there are many variations.

A whistler originates in a sferic. Although it has a complex fine structure, a sferic can be considered for analytical purposes to be a δ function: that is, a pulse of infinite amplitude and infinitesimal dura-tion containing a finite amount of energy. A δ function can be shown by a Fourier transformation to be equivalent to an infinite number of infini-tesimal signals distributed across the frequencies of the radio spectrum.

If the radio energy of a sferic travels in a dispersive region (that is, a region in which the index of refraction varies with frequency) then the time of arrival of the several frequency components will differ one from another. This is in fact what happens with whistlers: they travel through the exosphere in the lognitudinal propagation mode characterized by the index of refraction given in typical cases by Equation (26), and the time of arrival as a function of frequency varies typically as in Equation (27).

The identification of sferics with the origin of whistlers had been tentatively made prior to 1960, and the hypothesis advanced that their dispersion, in time, resulted from travel from hemisphere to hemisphere above the peak ionization region in the ionosphere in the mode character-ized by Equations (26) and (27). The technique of using a spectrogram-- a plot of whistler frequency vs time, used for quantitative analysis of

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propagation in the exosphere--had been adopted by then. But the positive identification of sferics with the origins of whistlers had not yet been made, and the analysis of whistlers had not been carried far enough to yield significant information on ionization in the exosphere.

Contributions reported by AFOSR in 1960--The only difficulty with the propagation mode described by Equations (26) and (27) is that, in a region of uniform ionization, it is unstable, as is shown by taking the derivative of (2) with respects to θ; for $\theta \ll \pi/2$,

$$dn^2/d\theta \doteq \omega_o^2 \big/ \theta \, \omega \, \omega_H > 0.$$

In other words, any small deviation of the ray path away from the magnetic field line is not automatically corrected, but tends to increase. Containment of the whistler signal along the magnetic lines of force requires magnetoionic "ducts" produced by electrons and ions circulating around the magnetic lines of force as described by Equations (18)-(24) [2622, 2623, 2624].[*]

When such a duct exists, it should allow propagation of whistlers in either direction--from southern hemisphere to northern and vice versa. Occasionally, therefore, a whistler should pass from north to south at the same time as one passing from south to north. Exceptionally, one or both of these simultaneous whistlers might be reflected, yielding a multiple series of whistlers at either end point. At either end point, each whistler signal should be more dispersed than the previous, because it will have traveled through the dispersive region one more time than the previous signal. That is, it will be slower than the previous signal in going from high to low pitch; in fact, the successive dispersal times required should be related as 1:2:3:.... Search of whistler recordings show that such series in fact exist [2621].

_____

[*] Numerals in square brackets are references to abstracts in the Air Force Scientific Research Bibliography, Vol. IV, op. cit.

As was brought out in connection with Equations (18)-(24), a uniform magnetic field does not change the magnitude of the velocity of a charged particle: the component of the particle parallel to the field is unaffected, and the component perpendicular to the field is unchanged in magnitude, but converted from a linear to a circular motion. The kinetic energy of the particle is, therefore, unchanged. The same is true in a magnetic field that changes slowly over space: the field constrains the motion of the particle, but does not change its kinetic energy. As the particle moves into a region of increased magnetic field, however, its transverse velocity increases. Its longitudinal velocity therefore must decrease; it may reach zero, and the particle is "reflected" where the field strength reaches a critical value dependent on its kinetic energy. Such a particle in the geomagnetic field in the exosphere is successively reflected at conjugate points in the northern and southern geomagnetic hemispheres. It cannot escape from the earth's magnetic field; and, conversely, the earth's magnetic field cannot have trapped such a particle in such an orbit, through nondissipative magnetoionic interactions. But such trapped particles can either extract energy from a whistler signal [2625] or amplify the whistler signal, as in a traveling-wave tube [2628]. It is the latter whistlers, of course, that are detected.

Since whistlers are often reflected many times back and forth between magnetic conjugate points, with increasing dispersion, it is often possible to extrapolate back from the whistler train and identify the individual sferic that originated the whistler [2626]. (Extensive studies took place in 1960, sponsored jointly by AFOSR and ONR and hence not reported here, comparing simultaneous recordings made at magnetic conjugate points positively to identify the sferic origins of many whistlers.)

As inspection of Equation (27) shows, the whistler signal spends most of its time where the gyrofrequency ω_H is least, and its total transit time is therefore a fairly accurate measure of electron concentration at the apex of its path. But Equation (27) fails for very high-altitude whistlers, because the gyrofrequency becomes comparable to the wave frequency. This gives rise to what is known as a "nose whistler," in which the whistler frequency has a minimum with respect to time, and may even rise slightly at the end.

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Spectrographic analysis of whistlers and nose whistlers....
and a new theory of the propagation path lead to the conclusion
that each component represents energy from the lightning source
which has been trapped in a field-aligned column of enhanced
ionization in the outer atmosphere. The data indicate that the
lifetime of these columns is a few hours. The theory suggests
that enhancements of about 5% are sufficient to explain the ob-
served whistlers. The theory further indicates that the aver-
age group velocity of energy trapped in a column can be closely
approximated by assuming that the energy travels along the
maximum of ionization in the column with wave normals aligned
with the magnetic field. The frequency of minimum time delay[*],
called the nose frequency, indicates the location of the field
line path. The minimum time delay gives a measure of the ioni-
zation density in the region near the top of the path. Exam-
ination of nose whistler data from a number of stations leads
to a model of electron density in the outer ionosphere.

[2627]

From nose whistlers a value of 100 electrons/cm^3 is calcu-
lated at 5 earth radii.

[2631]

Exceptionally, the nose frequency of a whistler can get low enough
to approach the gyrofrequency of protons, i.e., hydrogen nuclei. Care-
ful analysis of the dispersion of these low-frequency whistlers indicates
that the positive component of the exosphere out to 5 earth radii is
indeed ionized hydrogen.

Implications of AFOSR Contributions--Before 1960, the nature of
whistler propagation was understood, to the approximation involved in
Equation (1), and the fact realized that whistlers could yield information
about the exosphere. The major advances resulting from AFOSR-sponsored
work reported in 1960 were:

1.   Positive identification of sferics as the source of whistlers;

2.   Refinement of propagation theory to show that whistler propaga-
     tion required field-aligned ionization, and explaining explicitly
     the significance of "nose-whistlers";

---

*   This is an apparent error: the nose frequency is simply the minimum
    frequency. (J. E. Hacke, Jr.)

3. Analysis of whistler records to yield electron and proton densities out to 5 earth radii.

Whistler information proved to be the missing link between ionosonde measurements and satellite energetic particle count data that had led to postulation of the Van Allen belts. The inner belt, centered above the geomagnetic equator at an altitude of one-half earth radus (geocentric distance $1\frac{1}{2}$ earth radii) seems to result basically from the spontaneous decay of neutrons in cosmic rays reflected from the lower atmosphere by elastic collision. (Neutrons divide spontaneously into protons and electrons, releasing about 780 Kev energy.) Although the particle and energy flux is high, the particle density due to the radiation belt is but an insignificant increase in the total exosphere particle density.

The outer radiation belt, extending typically from about 3 to about 15 earth radii at the geomagnetic equator, varies in a complex manner with day, year, solar state, and geomagnetic disturbance. At least three mechanisms have been advanced to explain its formation:

1. Inward convection of protons on the night side of the lower exosphere could yield highly energetic particles by a magneto-hydrodynamic process analogous to adiabatic heating by compression.

2. The geomagnetic field lines through the upper radiation belt end in the auroral zones, and the hypothesis is therefore generally accepted that trapped radiation in the upper belt causes the aurora. Alternatively, protons from the solar wind may enter the auroral zones through two postulated polar "windows," and the outer belt may consist of protons reflected from the auroral zones by elastic collision with atmospheric species.

3. The passage of the earth through the solar atmosphere is known to produce a shock wave analogous to the bow wave of a round-bowed boat. This shock wave may heat particles of the solar atmosphere (mainly protons) enough to let them penetrate into the magnetosphere, where they dissipate enough of their energy by collision with thermal protons to become trapped.

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Through analysis of the variations in the outer radiation belts, of the geomagnetic field and of whistler records, a full and concrete picture of the magnetosphere has by now been constructed. "Magnetosphere" is a misnomer: the region is not even approximately spherical in shape. It is the region within which, with the possible exception of the polar "windows" just discussed, the particle flux from the sun (the "solar wind") is excluded from the vicinity of the earth. As seen from the earth, the solar wind has two components: the outward velocity of particles from the sun, and the eastward motion of the earth in its orbit. Toward the solar wind, the magnetosphere is compressed by the shock wave; in the other direction, it may extend 100,000 km.

The magnetosphere protects satellites, manned and unmanned, from the more energetic particle radiation from the sun, so long as they remain inside it and out of the radiation belts. Outside the magnetosphere, spacecraft are exposed to a proton flux measured by several U.S. and U.S.S.R. probes to involve 10^8 to 10^9 per cm^2 per second, traveling at velocities between 300 and 1000 km/sec. Magnetic storms and intense solar flares can increase the particle flux by an order of magnitude and increase particle energies to cosmic-ray values.

The existence of significant amounts of ionization out to several earth radii, and the fact that it varies both systematically and randomly, also is of significance for radar observations in the exosphere, satellite tracking, satellite geodesy, and microwave astronomy. Radio star scintillation yields some confirmation of the scale of electron density in the exosphere, and its rapidity yields statistical information on the rapidity of random variation and the scale of its spatial fluctuation [507].

Had the whistler phenomenon not been available as a tool for studying the exosphere, the information gleaned from whistlers could undoubtedly have been obtained in other ways: through appropriately orbited topside sounders, for example. But the topside sounders being planned prior to 1960 were to be orbited too low to have detected a significant portion of the ionization in the exosphere. Probes of the Van Allen belts, on the other hand, were instrumented to detect high-energy particle radiation,

not the thermal electron (and proton) constituents of the exosphere. The relatively complete and accurate picture of the magnetosphere and its constituents might have been delayed for several years had it not been for whistlers.

A whistler is a fairly potent electromagnetic probe. The energy in a quite ordinary thunderhead is of the same order of magnitude as a Hiroshima-type nuclear weapon, and a significant portion of that energy is radiated in a sferic. The sferic is an almost ideal ELF-VLF electromagnetic pulse. At any given time, there are perhaps 50 to 100 thunderstorms going on in the earth's atmosphere. The equipment required to detect and record whistlers is simple and inexpensive. What was needed was an understanding of the propagation of whistlers, positive identification of their sources, and analysis of sufficient records to map the electron density in the exosphere. Research sponsored by AFOSR and reported in 1960 made pioneering contributions in each of these areas.

Conclusions

1. In one specific instance, it has been demonstrated that research studies undertaken for the sake of investigation of a natural phenomenon, with no specific mission-oriented application in mind, has had major scientific impact and clear operational implications for the sponsoring agency.

2. It is a fallacy to think of scientific discoveries as linearly related, so that each discovery is indispensible to the next one. That is not the way in which science typically works. When a hypothesis is advanced to explain an observed phenomenon (e.g., significant electron density out to 5 earth radii to explain whistler propagation), the scientific community turns almost as if by instinct to seek out "independent verification" of the hypothesis (e.g., through the use of topside sounders).

3. For this reason, the appropriate question to ask of a scientific research project is not "What further discoveries did it make possible?" but "What further discoveries did it facilitate, and to what extent?"

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4. The conceptualization of the relationships between research, development, engineering, and exploitation on the basis of which this project was undertaken is confirmed in its broad outlines: whistler propagation, studied as a scientific phenomenon from about 1957 on, revealed information about the exosphere that was taken into account in assessing the feasibility of several space projects in the early 1960s, and in the design and execution of these projects in the late 1960s. But the conceptualization needs modification in detail to take into account the many possible interrelations between:

> theory
>
> instrumentation
>
> experimentation
>
> analysis
>
> hypothesis
>
> developmental engineering
>
> feasibility studies
>
> prototype engineering
>
> production engineering
>
> system performance engineering

Whistler data were significant in active communication satellite design, and they went almost immediately from feasibility study to operational incorporation in the worldwide telecommunication establishment.

For another example: As indicated earlier, microwave solar astronomy was one of the fields considered for anlaysis in this study, but it was eliminated because the work reported in 1960 consisted almost entirely of reports on the instrumentation and methods being developed; the AFOSR bibliography indicated little discussion of substantive microwave data from the sun. In addition, much of the reported work concerned the design and construction of large precision paraboloid antennas, and this field could not be considered non-mission related as far as the Air Force is concerned [2611, 2612, 2613, 2618].

The complete conceptualization must include at least the list of elements above, with feed back loops between many or all pairs of elements.

5. The identification of "phenomena-oriented research" with "non-mission-related research" and the precise delineation of each needs more explicit and exact delineation. As long as the Air Force has a space mission and the ocean is used for recovery of space vehicles, it is difficult to imagine any terrestrial, marine, atmospheric, space, or solar phenomenon not related at least indirectly to a possible Air Force mission. Perhaps "phenomena-oriented research" should be taken to refer to the research scientist's motivation, and "non-mission-related research" to the sponsor's. Whether the sponsor's motivation was mission-related or not might conceivably be deduced from the rationale advanced justifying the sponsorship of a specific project or for research in a specific disciplinary area.

6. The candidate fields for investigation in this study were rapidly narrowed by the requirement that the research be under exclusive AFOSR sponsorship. For this study, this rapid narrowing was not a disadvantage; but in a more extensive study it might be. The alternatives are to go behind the project to the levels of funding carried by the several sponsors, or broadening the scope of the study to include, for instance, all basic research sponsored by agencies of the Department of Defense. The former alternative entails an order-of-magnitude increase in the analytic effort required for the study, and the latter makes the problem of definition of "non-mission-related," discussed in Paragraph 5, more critical.

7. The analysis of the impact of a phenomenological investigation on the subsequent body of scientific knowledge is necessarily qualitative in view of the present state of the art of conceptual analysis. But the work of Goedel, Carnap, and the Vienna school of linguistic analysis may make it possible to diagram the conceptual structure of a scientific discipline and assess structurally the role of a set of research results in the discipline. For a discipline as complex as physics of the exosphere, a digital computer would undoubtedly be necessary for this analysis and assessment.

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8.   In the light of the preceding conclusions, and in spite of the limitations noted, the basic approach taken here of starting with the research *effort* and searching *forward* in time to its impacts is a valuable alternative to the more usual approach consisting of starting with a technological development and searching backwards for its origins in research or development.   The latter technique is likely to end at an invention, without asking the question, "Of what basic scientific discoveries is this invention an application?"

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13. ABSTRACT

This exploratory study has the purpose of developing and demonstrating methods of evaluating the scientific impacts of pioneering phenomena-oriented research sponsored by a mission-oriented agency. Analysis of research abstracts yielded an index of candidate research topics. Of these, three were selected as meeting all criteria; of the three, whistlers proved to contain the bulk of the scientific information.

Whistlers are audio-frequency radio signals resulting from the longitudinal propagation of sferics in the exosphere. Their general characteristics were fairly well understood prior to 1960; but work sponsored by AFOSR in that year contributed materially positive identification of their sources, understanding of the laws of their propagation, and elicitation of the information they yield about electron and proton concentrations at altitudes of up to 4 earth radii. As verified by other means, notably radio satellites, this information plays a pivotal role in understanding the exosphere, the radiation belts, the magnetosphere, and the limitations to earth-based radiolocation.

The study demonstrates the conclusion that working from scientific effort to scientific and technological impact is a valuable adjunct to analysis via the reverse path, and yields additional implications for the study of these impacts.